INFERENCES OF GRAVITY WAVE PROCESSES FROM ATMOSPHERIC SPECTRA

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ABSTRACT

Considerable information on the characteristics and variability of the atmospheric motion spectrum has emerged in the last few years. As a result, we are developing a much better understanding of the processes that maintain the spectral shape and account for spectral variability and its effects. This paper will summarize briefly some of the recent atmospheric spectral observations and their implications for gravity wave saturation processes, spectral shape, Doppler shifting, momentum fluxes, filtering and anisotropy. Also discussed are the apparent similarities and differences between the motion spectra in the atmosphere and the oceans.

INTRODUCTION

Gravity waves are now recognized by most researchers to account for the majority of the mesoscale motion field in the lower and middle atmosphere. Because of their ubiquity and their many effects, they have been the subject of considerable research efforts over the last few decades. Unlike the oceans, where the role of gravity wave motions in momentum and energy transports is at present uncertain, atmospheric gravity waves are now believed to be responsible for much of the vertical coupling of momentum and energy in the atmosphere.

Much of our knowledge of gravity wave motions in the atmosphere has come from remote sensing using ground-based radar or optical systems. Also available, however, has been a range of in situ data obtained with balloon, aircraft, space shuttle, rocket, satellite and other instrumentation. These data have yielded many insights into the structure and variability of the atmospheric motion field. Radar and lidar systems have provided data on the temporal nature and vertical structure of atmospheric motions at one location. High-resolution vertical profiles have also been obtained with balloon- and rocket-borne systems, while data on the horizontal variability and/or vertical structure of the motion, thermal, and constituent fields have been provided by balloon, aircraft, space shuttle, and satellite instrument systems. Together, these data provide an increasingly comprehensive picture of the processes controlling the atmospheric gravity wave spectrum and its various effects.

One intent of this paper is to summarize some of the more general implications of the diverse spectral observations of atmospheric motions that are now available. A second objective is to note some of the areas in which atmospheric and oceanic processes are likely to be similar and those where we should expect to see disparities. Characteristics of and inferences drawn from vertical wavenumber spectra at various levels in the atmosphere are presented in the following section. The principal result here is that several processes are acting to control the amplitude of the spectrum to a remarkable degree. We then examine the implications of frequency spectra of horizontal and vertical motions for wave propagation, Doppler shifting, and wave field anisotropy. Additional evidence of anisotropy, and of the extent to which gravity waves force the larger-scale atmospheric circulation, is provided by momentum flux and divergence measurements at a range of sites. Recent studies have also emphasized the scales at which these fluxes are preferentially contained. We conclude with a discussion of the similarities and differences of atmospheric and oceanic spectra and processes.

VERTICAL WAVENUMBER SPECTRA

Vertical wavenumber spectra of horizontal motions and density or temperature fluctuations obtained during the last few years increasingly have been interpreted as evidence of gravity wave saturation. Initially, it was argued by Dewan and Good (1986) and Smith et al. (1987) that linear instabilities should dictate a saturated spectrum at large vertical wavenumbers with horizontal velocity and fractional temperature spectra varying as $\sim N^2/6\ m^3$ and $N^4/10\ g^2 m^3$. More recently, other saturation mechanisms have been investigated and explanations of the saturated spectrum offered based on nonlinear interactions and/or Doppler shifting (Dong and Yeh, 1988; Hines, 1988; Holloway, 1988; Dunkerton, 1989; Fritts, 1989; Fritts and Yuan, 1989a; Hines, 1991). In all cases, however, these theories have predicted amplitudes and slopes largely consistent with linear theory. This suggests that the implications of gravity wave saturation will be more dependent on spectral character than on specific saturation processes.

At lower wavenumbers, vertical wavenumber spectra are expected to have a positive slope to insure a finite vertical flux of wave action (VanZandt and Fritts, 1989). Consistent with the increase in energy density (per unit mass) with height and the amplitude limits at large wavenumbers, horizontal velocity spectra exhibit a dominant vertical wavenumber $m_* = 2\pi/\lambda_{z*}$ that decreases with increasing height from ~ 3 rad/km in the troposphere and lower stratosphere (Fritts and Chou, 1987; Fritts et al., 1988; Tsuda et al., 1989) to ~ 0.3 rad/km near the mesopause (Smith et al., 1987; Wu and Widdel, 1989). The increase in energy density with height is generally attributed to a preferential upward propagation of gravity wave energy and the associated decrease in atmospheric density. Similar slopes and amplitudes were noted in stratospheric temperature spectra (Fritts et al., 1988) obtained with high-resolution balloon soundings. Lidar data, in contrast, yield spectra with similar slopes, but with amplitudes that depart from those predicted by saturation theory in the middle stratosphere (Chanin and Hauchecorne, 1987; Kwon et al., 1990), due perhaps to the longer integration times inherent in the lidar profiles and a lack of sensitivity to motions near inertial frequencies which contain the majority of the velocity and temperature variances.

A spectral form that appears to fit well the various observations is

$$E(m) = \frac{4E_0}{\pi m_*} \frac{m/m_*}{1+(m/m_*)^4}, \qquad (1)$$

where E_0 is the total spectral variance and m_* is the characteristic vertical wavenumber corresponding to the wavenumber of maximum spectral density in a variance content form. To be consistent with the saturated spectral amplitudes estimated by Smith et al. (1987), this implies $E_0 = \pi N^2/24\ m_*^2$ and $E_0 = \pi N^4/40\ g^2 m_*^2$ for velocity and fractional temperature fluctuation spectra, respectively.

A vertical wavenumber spectrum with the above characteristics has a number of implications for atmospheric circulation and structure. First, a form given by Eq. (1) with a decrease of m_* consistent with observations implies a growth of wave energy at small wavenumbers that is less than expected for conservative motions (Smith et al., 1987) and thus a continuous removal of energy from motions at all vertical scales. This implies, in turn, smooth variations of wave energy and momentum flux, and of their vertical divergences, with height and corresponding smooth variations in wave drag and induced diffusion. Because the saturated spectral amplitude depends on the buoyancy frequency, N, we also anticipate additional, or enhanced, saturation and effects near regions where N^2 increases with height. This implies increased wave dissipation and drag above the tropopause and the summer mesopause, in particular, that can be estimated based on the observed spectral character (VanZandt and Fritts, 1989). These effects are expected to be especially important at greater heights where the wave energy and momentum flux divergences have greater influences.

Temporal variations of the vertical wavenumber spectrum provide evidence of isolated components of the motion field and thus may suggest the processes primarily responsible for wave saturation in the atmosphere. Shown in Figure 1 are series of vertical wavenumber spectra in variance content form in the troposphere and lower stratosphere at 1-h intervals obtained with the MU radar in Japan (Fritts et al., 1988). The spectra reveal good consistency with height and significant local departures from the canonical form of the saturated vertical wavenumber spectrum. Of particular interest, however, are the persistent features both near the maxima and at higher vertical wavenumbers that suggest long-lived components of the motion spectrum propagating and dissipating in superposition, but without interaction, with other spectral components. This seems to imply a dissipation process that relies on local wave field instabilities due to superposed wave amplitudes rather than strong wave-wave interactions and spectral energy transfers.

Additional evidence of wave instability and turbulence generation is provided by measurements of spectral characteristics at smaller scales. One example of a vertical wavenumber spectrum of neutral density fluctuations inferred with a rocket-borne positive ion probe (PIP) during the MAC/EPSILON experiment is shown in Figure 2 and exhibits three distinct spectral ranges (Blix et al., 1990). At scales larger than ~ 300 m the spectrum has a slope near -3, consistent with the large wavenumber range expected for saturated gravity wave motions. From scales of ~ 5 - 300 m, however, the spectrum has a slope near -5/3, suggesting inertial range turbulence and wave energy dissipation. Finally, at scales less than ~ 5 m, the spectrum appears to be consistent with a

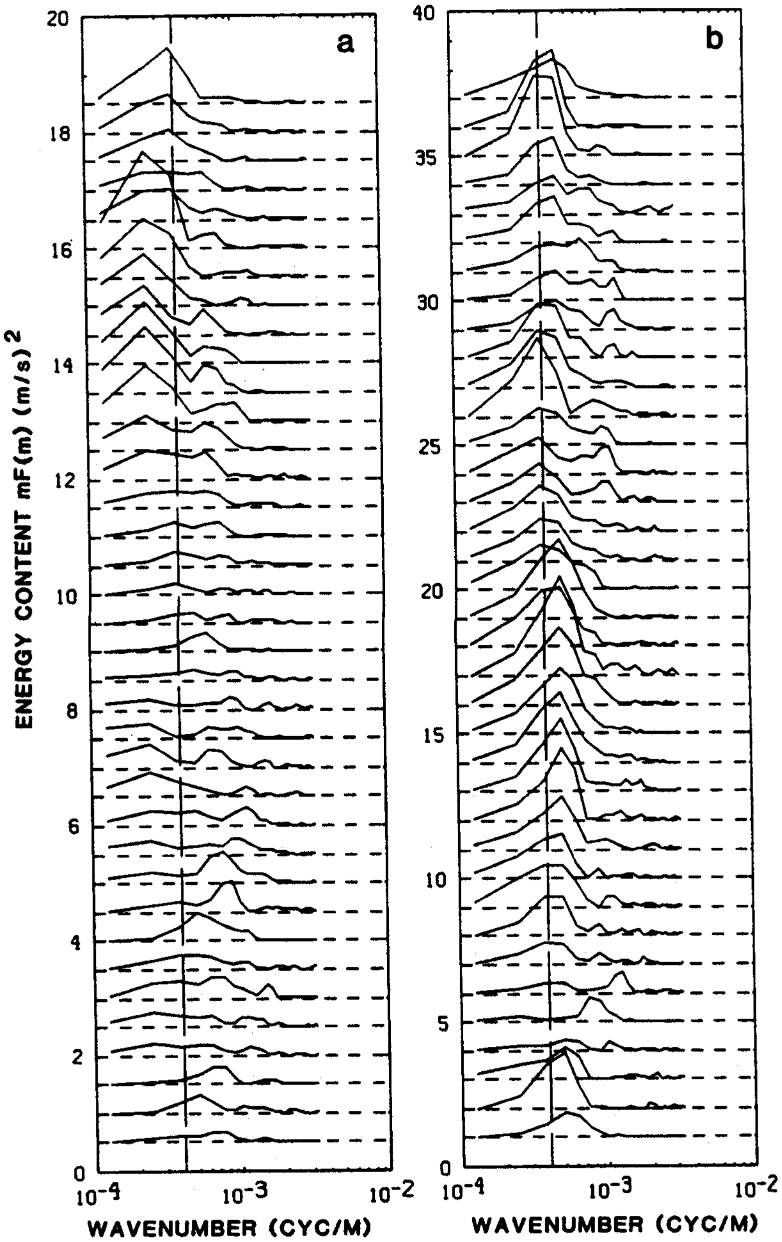

Figure 1. Hourly area-preserving spectra of northward radial velocity for (a) 5 - 13 and (b) 13 - 20.5 km heights with time increasing upward (Fritts et al., 1988). Note the consistency and persistence of spectral features in time and the departures from canonical form.

viscous subrange. Spectra obtained on other rocket flights provide similar views of small-scale dynamics and imply that these spectral features are persistent components of the motion field. These spectra imply a nearly continuous transfer of energy from gravity wave motions through inertial range turbulence to viscous scales. Estimates of the energy dissipation rates may be obtained from the transition scales and from the spectral amplitude within the inertial range, leading to estimates of ~ 0.01 W/m^2 in the middle and upper mesosphere. Estimates using radar techniques suggest comparable values, with enhancements near the summer mesopause that are consistent with predictions of saturation theory.

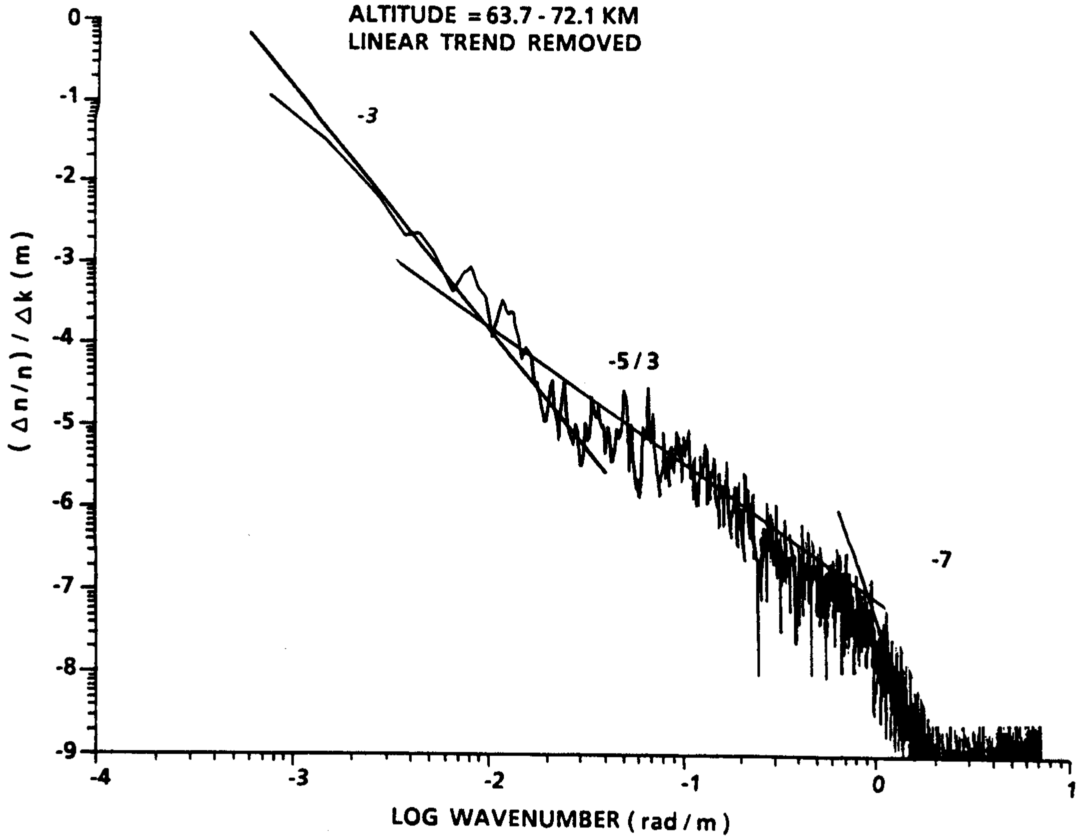

Figure 2. Spectrum of density fluctuations obtained with a positive ion probe showing three spectra ranges between scales of ~ 3 m and 8 km (Blix et al., 1990). These suggest ranges consistent with gravity wave saturation, inertial range turbulence, and viscous dissipation.

FREQUENCY SPECTRA OF HORIZONTAL AND VERTICAL MOTIONS

Measurements of frequency spectra using various techniques have revealed the general characteristics and variability of the motion field under a variety of conditions. Frequency spectra obtained using atmospheric radars have provided the greatest diversity of observations and have shown the mean frequency spectrum of horizontal motions to exhibit an amplitude growth with

increasing height and clear tidal peaks at upper levels. At frequencies greater than tidal frequencies, most observations suggest a slope near -5/3 (Balsley and Carter, 1982; Vincent, 1984) that is nearly invariant with height and mean atmospheric motions. Observations of frequency spectra of vertical motions are more varied, with slopes that are slightly positive under weak wind conditions and which become increasingly negative as mean winds increase. Examples of vertical velocity spectra under weak and strong wind conditions are shown for reference in Figure 3.

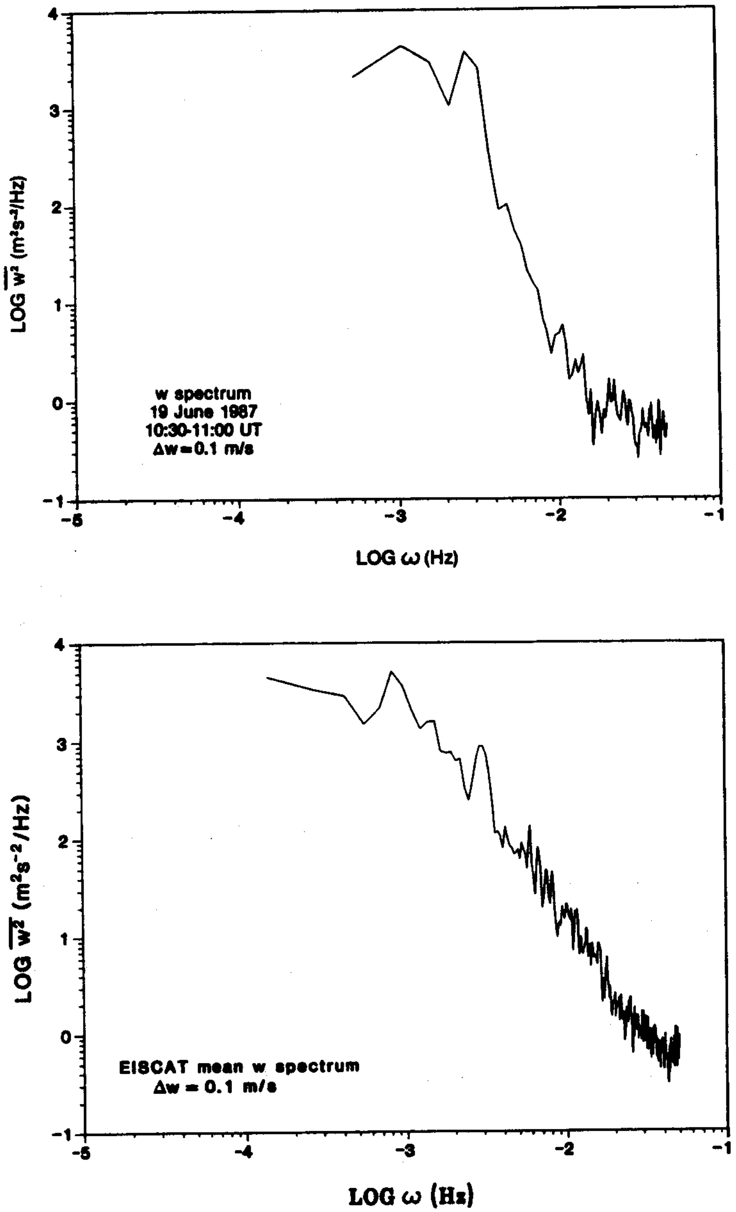

Figure 3. Vertical velocity frequency spectra during the MAC/SINE campaign (Fritts et al., 1990a). Upper plot is for light winds and exhibits a peak near N. Lower plot is a mean spectrum.

Assuming that the frequency and wavenumber spectra of gravity wave motions are separable, for which there is some evidence, and an intrinsic frequency spectrum (relative to the medium) of horizontal motions of the form ω^{-p}, with $p \sim 5/3$, we expect the intrinsic frequency spectrum of vertical velocities to vary as ω^{2-p}. These expectations are in agreement with observations under light wind conditions, but depart significantly when mean horizontal motions are large.

Departures of the observed spectra from the anticipated forms of intrinsic frequency spectra may arise for several reasons. As noted in the previous section, vertical wavenumber spectra exhibit substantial departures from the mean spectral form and suggest that similar variability might be expected to occur among frequency spectra as well. But this explanation is unable to account for departures of mean spectra from a relationship consistent with the gravity wave dispersion relation. Instead, these departures appear to be due to the differing effects of Doppler shifting on the frequency spectra of horizontal and vertical motions (Fritts and VanZandt, 1987).

The importance of Doppler shifting depends on 1) the relative motion of the intrinsic and observed frames, 2) the horizontal wavenumbers and phase speeds of the motions containing the majority of the spectral variance, and 3) the direction of wave propagation relative to the mean motion. If the mean motion is small compared to characteristic phase speeds or intrinsic frequencies are small, as is generally the case for those gravity waves accounting for most of the horizontal velocity variance, then Doppler shifting effects are relatively minor and wave propagation directions are unimportant. If, however, the mean motion is large compared to phase speeds containing the velocity variance or intrinsic frequencies are high, then there is a large potential for Doppler shifting of velocity variance throughout the spectrum and wave propagation directions are very important.

More simply stated, it is easier to Doppler shift velocity variance from high to low frequencies than from low to high frequencies (a mean flow comparable to the intrinsic phase speeds can Doppler shift high-frequency variance to $\omega \sim 0$, but not vice versa). This implies much greater differences in the intrinsic and observed frequency spectra for vertical motions (primarily at high frequencies) than for horizontal motions (primarily at low frequencies) and suggests that vertical velocity spectra will be more sensitive to such effects as a result. The effects of Doppler shifting on two-dimensional, symmetric, idealized, intrinsic horizontal and vertical velocity spectra (with $p = 2$) are illustrated in Figure 4 for various values of $\beta = u/c_*$, where u is the relative motion, $c_* = N/m_*$, and m_* is as defined with Eq. (1). These results demonstrate that the slopes of observed symmetric horizontal velocity spectra remain nearly constant at high frequencies, even for large β, while observed vertical velocity spectra may exhibit significant changes in slope and amplitude at small β.

The significant changes anticipated theoretically in observed vertical velocity spectra under different Doppler-shifting conditions provide a convenient test of these simple spectra effects. Such tests have been performed by Vincent and Eckermann (1990), VanZandt et al. (1990), and Fritts and Wang (1991) and reveal a remarkable consistency with the theory, suggesting that

Doppler-shifting effects do indeed account for much of the observed spectral variability. Vincent and Eckermann (1990) noted that Doppler-shifting appeared to explain the increase in wave variance parallel to the local flow associated with frontal circulations and VanZandt et al. (1990) found good agreement between model predictions and observed, symmetric spectra in the lower atmosphere. At greater heights, Fritts and Wang (1991) found observed vertical velocity spectra to provide evidence of Doppler shifting, wave field anisotropy, and the form of the vertical wavenumber spectrum. These results suggest that observed motions are largely consistent with gravity wave theory and differ from the predictions of geostrophic or stratified turbulence, which has been offered as an alternative explanation of the motion field (Gage, 1979; Lilly, 1983).

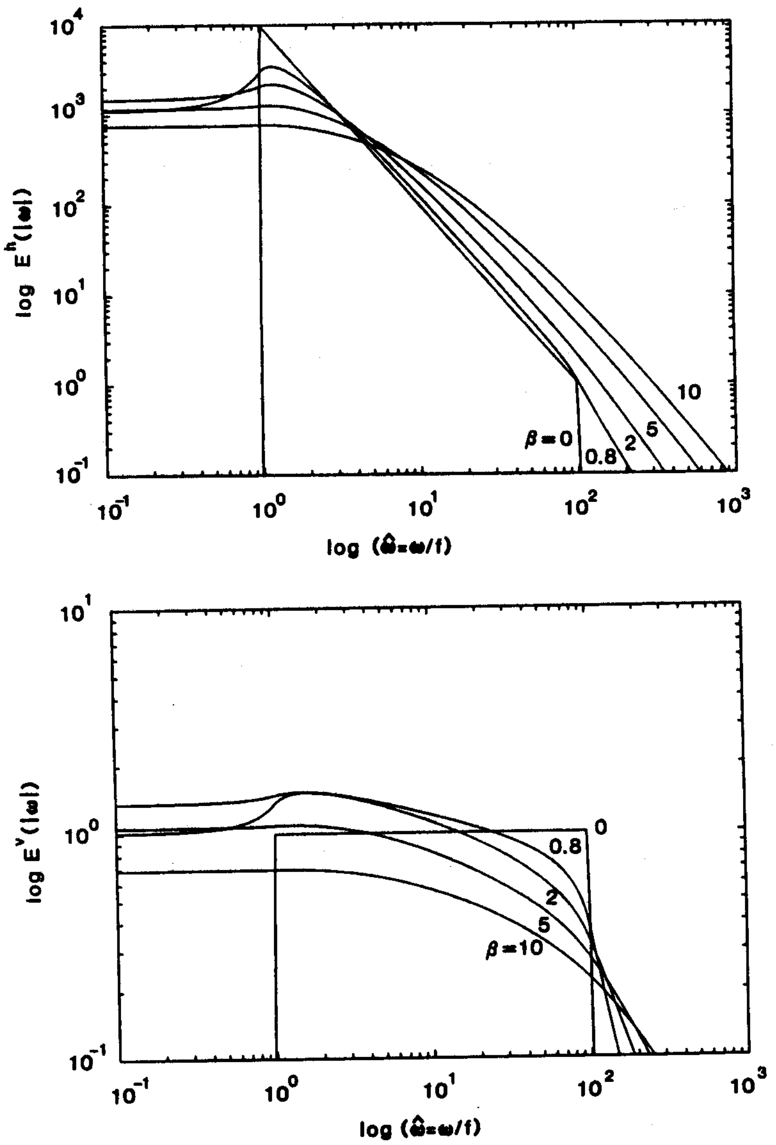

Figure 4. Effects of Doppler shifting on two-dimensional isotropic horizontal and vertical velocity spectra (Fritts and VanZandt, 1987). See text for parameters.

The observed, and inferred intrinsic, frequency spectra also have implications for the dominant transport processes within the gravity wave field. As noted by Fritts (1984), the forms of the observed frequency spectra of horizontal and vertical velocities imply that wave energy and momentum fluxes are accomplished primarily by motions with high intrinsic frequencies. While horizontal velocity variance (and thus total wave energy) resides mainly at low intrinsic frequencies, $\omega \sim f$, momentum and energy fluxes depend on the speed of vertical propagation, causing the major fluxes to be associated with motions with intrinsic periods < 1 h. These motions were estimated to provide ~ 70 % of gravity wave transports by Fritts (1984). Subsequent observations at a number of sites have served to confirm these estimates at lower and upper levels (Fritts and Vincent, 1987; Reid and Vincent, 1987; Reid et al., 1988; Fritts and Yuan, 1989b; Fritts et al., 1990b; Wang and Fritts, 1990). More will be said about the spectral character of gravity wave momentum fluxes in the following section.

MOMENTUM FLUX SPECTRA

Relative to velocity spectra, there are very few observational data at present on the spectral character of momentum fluxes. Those that are available, nevertheless, serve to confirm our expectations based on velocity spectra, integrated momentum flux measurements, and theory.

One example of the observed frequency spectrum of vertically averaged westward momentum flux computed from the difference of averaged radial velocity spectra is shown in Figure 5 in standard and flux content form (Fritts et al., 1990b). This spectrum suggests a dominance of the

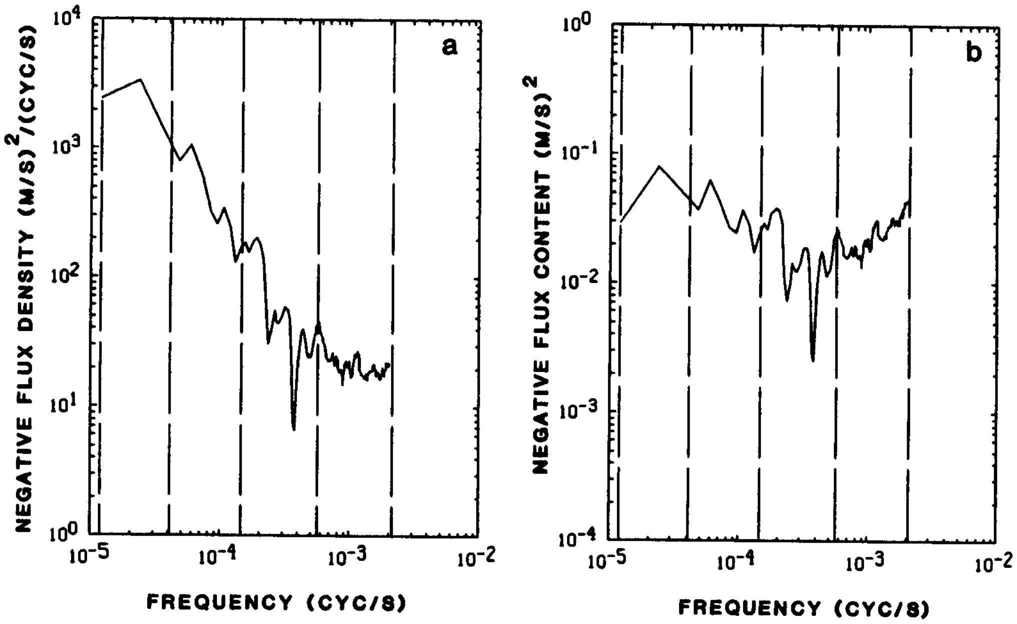

Figure 5. Frequency spectrum of vertically averaged westward momentum flux obtained with the MU radar (Fritts et al., 1990b) in (a) standard and (b) flux content form.

total momentum flux by low-frequency motions. As noted by Fritts et al. (1990b), however, the disparate radial velocity variances imply high intrinsic frequencies despite the small observed frequencies and thus wave motions and momentum fluxes largely consistent with orographic excitation. This view is supported as well by the temporal variability of the vertically averaged westward momentum flux observed in that data set.

It is not possible to obtain an accurate estimate of the intrinsic frequencies accounting for a majority of momentum fluxes at one site without knowledge of the horizontal scales and/or the relative anisotropy of the motion field. Such an estimate is possible, however, with horizontal measurements of wave activity and covariances in circumstances in which wave phase speeds may be reasonably approximated. This occurs when we expect the predominant wave motions to be due to orography, as in the observations of variance enhancements associated with orography by Nastrom and Fritts (1991). The momentum flux spectra (or cospectra of u and w) obtained from four aircraft flights during the the Global Atmospheric Sampling Program (GASP) are shown in standard and variance content form in Figure 6. These reveal, consistent with the inferences drawn from the MU radar data, that the majority of the momentum flux is due to motions with small horizontal scales and relatively high intrinsic frequencies. With the major contributions at horizontal scales of ~ 20 - 60 km and mean flows of ~ 20 m/s, we infer characteristic intrinsic periods of < 1 h. These results are also in agreement with momentum flux observations at greater heights for which orographic influences are likely to be less pronounced (Fritts and Vincent, 1987; Reid and Vincent, 1987; Fritts and Yuan, 1989b; Reid et al., 1988; Wang and Fritts, 1990).

The occurrence of the primary gravity wave momentum fluxes at small horizontal scales and high intrinsic frequencies has some important implications for the forcing of the large-scale

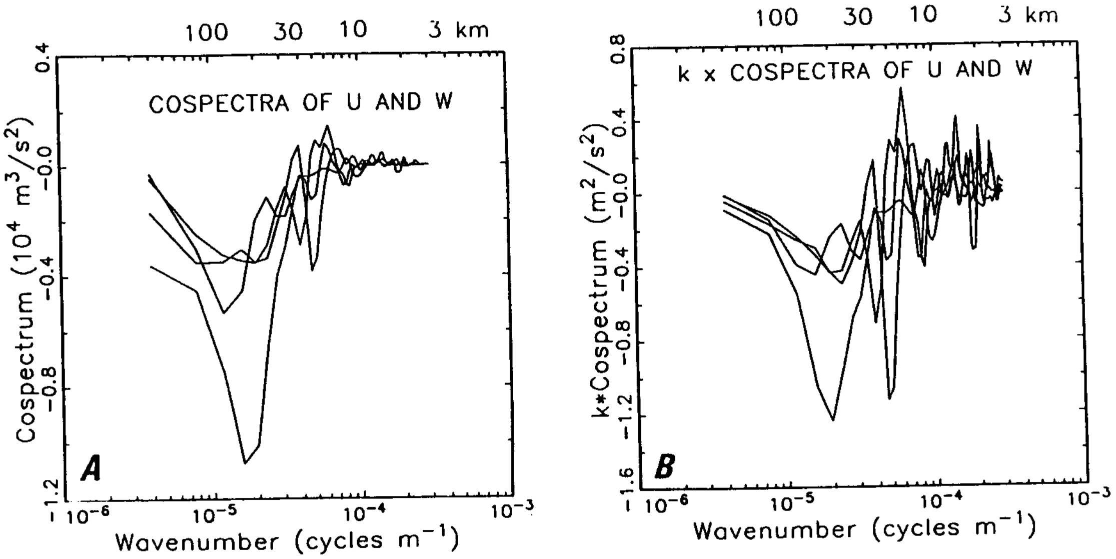

Figure 6. Momentum flux versus wavenumber in (a) standard and (b) flux content form (Nastrom and Fritts, 1991). Integrated values are negative with the major contributions at < 100 km scales.

atmospheric circulation and structure. Because such gravity waves have relatively steep propagation paths and the sources of such motions are often episodic and highly localized (Fritts and Nastrom, 1991), we might expect that the forcing of the mean state accompanying wave dissipation will also have similar attributes. This suggests that the response of the middle atmosphere to gravity wave excitation at and propagation up from lower levels will reflect the source and filtering conditions in place at that site, with horizontal coupling over large distances playing a much smaller role. These effects are particularly important in assessing the role of gravity wave forcing of the middle atmosphere because of the large mean fluxes that have been observed and the significant influences on the large-scale circulation and structure that are implied.

COMPARISON OF ATMOSPHERIC AND OCEANIC SPECTRAL IMPLICATIONS

Gravity wave spectra in the atmosphere and oceans share many features due to common source, propagation, and dissipation processes. There are also, however, some important differences between atmospheric and oceanic spectra that arise due to quantitatively different source distributions, wave-wave and boundary interactions, and characteristics of the mean wave environment.

Tidal and inertial-scale forcing of the oceanic internal wave spectrum by surface winds and currents over orographic features acts to energize near-inertial frequencies and results in a pronounced peak in wave energy near $\omega \sim f$. These motions persist for long times, may propagate large distances, and interact with other components of the spectrum on (arguably) slow time scales, resulting in an oceanic spectrum in the frequency and wavenumbers domains that is nearly universal in shape and amplitude. Because dissipation processes are slow away from boundaries and the wave spectrum is confined between two largely reflecting surfaces, there is also a tendency for the spectrum to be nearly vertically symmetrized and for net vertical fluxes of energy and momentum to be small. Under these conditions, the motion field can be conveniently expressed using a modal description.

Atmospheric gravity waves, in contrast, are excited by a wide range of source processes that appear to contribute wave energy predominantly at intermediate and high intrinsic frequencies. These include convective and frontal processes, orography, and wind shear and lead to atmospheric frequency spectra that do not include an inertial spike characteristic of the oceanic spectra. This greater fraction of total wave energy at higher frequencies in the atmosphere implies several important differences in atmospheric and oceanic spectra.

Wave motions at higher intrinsic frequencies propagate vertically more rapidly than low-frequency motions at comparable vertical scales. This results in larger vertical fluxes of energy and momentum and greater flux divergences (and associated energy dissipation and body forces) in regions of wave dissipation than would accompany lower-frequency motions. The effects of these transports are enhanced in the atmosphere at heights above the primary wave sources due to the exponential decay of density with height, which causes wave amplitudes to increase approximately exponentially with height and energy and momentum fluxes and their divergences to increase relative to background levels. Energy dissipation rates (measured relative to local energy densities) in the stratosphere and mesosphere are consequently much larger than in the ocean and imply dissipation time scales for gravity waves of ~ 10 - 100 times less than in the oceans (~ hours - 10's of hours rather than ~ 10's of days). This likewise suggests differences in the processes acting to remove energy from the wave spectrum, requiring fast, energetic dissipation at increasing heights in the atmosphere (primarily local convective instability) and permitting slower and/or more systematic energy transfers (primarily dynamical instability or wave-wave interactions) at lower levels of the atmosphere and in the oceans. Despite the different physical processes suggested to be responsible for wave dissipation in the oceans and at various heights in the atmosphere, all those processes considered viable lead to comparable limits on wave amplitudes and corresponding saturated wavenumber spectra. Similar arguments imply that gravity wave momentum fluxes play a more significant role in forcing the large-scale circulation and structure in the middle and upper atmosphere than in the oceans.

Another difference between atmospheric and oceanic spectra that is due in part to the distribution of wave energy with frequency and in part to differences in the wave environment is the relatively greater influence of Doppler shifting in observed spectra of atmospheric motions. As noted previously, motions with intrinsic frequencies that are high are easily Doppler shifted to observed frequencies that are low, while low-frequency motions cannot be shifted to observed frequencies that are high. Additionally, typical mean motions of the atmosphere are larger than characteristic wave phase speeds, particularly at lower levels, whereas oceanic wave phase speeds are generally greater than mean currents. This results in a much greater range of observed frequency spectra, especially of vertical velocities because of their greater sensitivity (their greater energy concentration at $\omega \sim N$), in the atmosphere than in the oceans. The larger characteristic anisotropy of the atmospheric gravity wave field (due to discrete, high-frequency sources and greater departures from vertical symmetry) also contributes to variations of frequency spectra of horizontal and vertical velocities and permits inferences of wave sources, filtering, and effects that appear to be more challenging in the oceans.

In summary, the physical processes acting to excite, mould, and dissipate the gravity wave spectra in the atmosphere and oceans have some similarities and some important differences. The similarities account, broadly, for the qualitative agreement in mean observed frequency and wavenumber spectra in the two systems (spectral slopes and apparent saturation limits). But there are large differences in the potential for energy and momentum transports, dissipation processes, anisotropy, and influences on the mean state due to the unbounded and exponentially decreasing mean density in the atmosphere, the vertically contained and more vertically uniform mean structure of the oceans, and the very different intrinsic frequencies at which primary wave excitation occurs in the atmosphere and oceans.

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